PB89-118517

Measurement of Dry Deposition Using Imperfect Sensors and in Non-Ideal Terrain (Journal Version)

(U.S.) National Oceanic and Atmospheric Administration, Oak Ridge, TN

Prepared for

Environmental Protection Agency
Research Triangle Park, NC

1988

U.S. Department of Commerce
National Technical Information Service
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1. REPORT NO. EPA/600/J-88/160	2.
3.	PB89-118517
4. TITLE AND SUBTITLE: ON THE MEASUREMENT OF DRY DEPOSITION USING IMPERFECT SENSORS AND IN NON-IDEAL TERRAIN (Journal Version)	5. REPORT DATE: 1988
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S): B. B. Hicks and R. T. McMillen	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS: NOAA/ERL Air Resources Laboratory, Atmospheric Turbulence & Diffusion Division, P. O. Box E, Oak Ridge, Tennessee 37831	10. PROGRAM ELEMENT NO. CCVN1A/07 - 3014 (FY-85)
	11. CONTRACT/GRANT NO. IAG #DW13930073
12. SPONSORING AGENCY NAME AND ADDRESS: Atmospheric Sciences Research Laboratory-RTP, NC, Office of Research and Development, U. S. Environmental Protection Agency, Research Triangle Park, North Carolina 27711	13. TYPE OF REPORT AND PERIOD COVERED: Journal Article
	14. SPONSORING AGENCY CODE: EPA 600/09

15. SUPPLEMENTARY NOTES

Boundary-Layer Meteorology, 42:79-94, 1988

16. ABSTRACT

Important questions concerning the turbulent exchange of atmospheric pollutants between the air and natural surfaces urgently require answers, but sensors for many important species are not yet sufficiently well developed for use with standard micrometeorological methods. There is need, therefore, to develop methods by which deficient sensors can be used in micrometeorological applications. There is also need to extend micrometeorological methods to circumstances which do not satisfy the conventional perfect-site constraints. Here, methods based upon the assumption of cospectral similarity are explored. Initial tests indicate that it is possible to estimate daytime turbulent fluxes with sensors having response times considerable greater than the values normally quoted (e.g. 5 s instead of 1 s), and to compute first-order corrections for the error resulting from the lack of detection of high-frequency turbulence. It is suggested that a similar method might be used to derive flux data in terrain more complex than can be handled by conventional micrometeorology. The techniques outlined here can be applied only with caution, but appear adequate to permit the use of deficient sensors in some circumstances, and good sensors over some micrometeorologically deficient terrain.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

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U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL INFORMATION SERVICE
SPRINGFIELD, VA. 22161

18. DISTRIBUTION STATEMENT: RELEASE TO PUBLIC	19. SECURITY CLASS (This Report): UNCLASSIFIED	21. NO. OF PAGES: 18
	20. SECURITY CLASS (This page): UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (9-73)

EPA/600/J-88/160
JOURNAL ARTICLE

ON THE MEASUREMENT OF DRY DEPOSITION USING IMPERFECT SENSORS AND IN NON-IDEAL TERRAIN

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(Received in final form 23 July, 1987)

Abstract. Important questions concerning the turbulent exchange of atmospheric pollutants between the air and natural surfaces urgently require answers, but sensors for many important species are not yet sufficiently well developed for use with standard micrometeorological methods. There is need, therefore, to develop methods by which deficient sensors can be used in micrometeorological applications. There is also need to extend micrometeorological methods to circumstances which do not satisfy the conventional perfect-site constraints. Here, methods based upon the assumption of cospectral similarity are explored. Initial tests indicate that it is possible to estimate daytime turbulent fluxes with sensors giving response times considerably greater than the values normally quoted for eddy correlation (e.g., 5 s instead of 1 s), and to compute first-order corrections for the error resulting from the lack of detection of high-frequency turbulence. It is suggested that a similar method might be used to derive flux data in terrain more complex than can be handled by conventional micrometeorology. The techniques outlined here should be applied only with caution, but appear adequate to permit the use of deficient sensors in some circumstances, and good sensors over some micrometeorologically deficient terrain.

1. Introduction

A major goal of micrometeorological research has been to develop a method for determining the atmosphere-surface exchange rates of properties that affect the behavior of the atmosphere, primarily momentum, heat, and water vapor. This focus has been broadened in recent years to include trace gas and particle exchange, as a result of steadily increasing concerns about air pollution and its consequences. In response to the need for information on exchange rates of trace chemical species, techniques developed earlier for studies of Reynolds stress and heat exchange (both sensible and latent) have been extended, wherever possible, to the cases of trace gases such as carbon dioxide, ozone, sulfur dioxide, and nitrogen oxides, and sometimes to particles. 'Dry deposition' can be considered a subset of the overall topic of atmosphere-surface chemical exchange, which is itself an extension of more classical considerations of turbulent fluxes. As discussed here, dry deposition is the turbulent exchange of trace gases and small particles from the atmosphere to the surface.

Recent progress in research on surface fluxes of trace chemical species is following similar lines of development as for past studies of heat and moisture exchange, although the pace is far more rapid. Conventional micrometeorological studies of turbulent exchange have needed to confront similar problems to those now being addressed in studies of dry deposition. For example, many innovative methods have been suggested to permit measurements to be made (even imprecisely) in demanding conditions. The so-called NIFTI technique (Hicks and Dyer, 1972; Dyer, 1975) is of special relevance

Boundary-Layer Meteorology **42** (1988) 79–94.

ATDL Contribution File no. 85/34

here, since it was intended to address a situation in which questions of both sensor limitations and imperfect exposure arose. The similarity methods addressed here are a further step along this line of development, occasioned by the urgent need to evaluate surface fluxes of trace chemical species in experimentally demanding situations.

In the following section, we shall attempt to clarify the difference between the experimental needs for intensive research studies and for monitoring. In subsequent sections, we shall address the experimental limitations imposed in the application of normal micrometeorological methods, and will propose methods based on cospectral similarity as a possible practical solution. The surface heat energy budget is then proposed as a means to avoid the need for a detailed micrometeorological component. Effects of signal noise are then examined in the context of noise levels associated with practical air pollution sensors. Some preliminary experimental results are presented, and relationships permitting canopy heat storage to be taken into account are given. Finally, we shall present results of a series of field trials designed to test the technique, using water vapor as a surrogate.

2. Requirements for Research and Monitoring

It is useful to differentiate between those techniques being developed for routine use in dry deposition monitoring activities, and those suitable for more limited application in research investigations of dry deposition processes. In the former category, emphasis is usually placed on the interpretation of air concentration data, while recognizing that such inferential methods are deficient; appropriate deposition velocities are not always available and fluxes are not always directed towards the surface. A basic goal of many research programs is to extend the present limited knowledge of deposition velocities (and the factors that control them) to circumstances and chemical species outside the range of current knowledge. Most of the techniques of deposition measurement included in the latter category of research methods are intended for use in investigations of the deposition velocity, rather than in programs to evaluate deposition fluxes routinely.

The immensity of the problem is obvious. Deposition velocities are not only species-specific, but also surface-dependent and time-varying. In essence, the deposition velocity problem can be viewed in terms of a three-dimensional array, ordered by the kind of pollutant, by the type of surface, and by the meteorological situation. The task is too great to produce direct experimental evidence corresponding to all available elements in such an array. Instead, the research programs are trying to provide coverage over most of the array and to minimize the need for unguided interpolation.

Hicks (1979) addresses the matter of pollutant sensing requirements for micrometeorological applications. Several distinctly different factors complicate the way in which micrometeorological gradient methods can be applied to measure dry deposition rates. First, gradient methods require the use of sensors capable of resolving differences with 1% precision, or better. This requirement is sufficiently demanding that field experiments employing gradient methods are relatively rare, and are often comparatively unproductive. Second, gradient methods usually require the specification of an

appropriate turbulent diffusivity. Over simple surfaces (e.g., relatively smooth surfaces such as grass), diffusivities can be computed from supporting wind and temperature gradient measurements by applying well-accepted flux-gradient relations that account for effects of surface roughness and atmospheric stability. However, in many situations of steadily increasing practical importance (e.g., forest canopies) the applicability of these flux-gradient relations is open to question. Over trees, eddy diffusivities describing pollutant transfer cannot be assumed to be the same as for water vapor, heat or momentum (see Garratt, 1978; Hicks *et al.*, 1979). The Bowen ratio approach (e.g., Kanemasu *et al.*, 1979) is often used as a practical method to bypass this particular problem; by relating all measurements to a flux which can be measured with confidence (the net radiation), the need for a precise determination of eddy diffusivity is eliminated. However, further difficulties then arise with the need to account for heat storage in the canopy, as will be discussed later.

Eddy correlation techniques do not require an assumption regarding eddy diffusivity, and hence tend to be preferred. However, the fast-response sensing requirement limits the application to very few chemical species. In general, $\pm 10\%$ evaluations of eddy fluxes require 1 s response time in daytime conditions, and sometimes as short as 0.1 s at night. For most pollutant species, deposition occurs mainly in daytime and hence the requirement communicated by micrometeorologists to those developing new chemical sensors most often concerns the need for response times of one second or shorter.

Eddy correlation appears to be preferred whenever suitable instrumentation is available. However, gradient methods provide the only available micrometeorological alternative for many pollutants which cannot yet be measured rapidly enough for eddy correlation, such as nitric acid vapor (Huebert and Roberts, 1985).

The history of development of micrometeorological measurement methods has cast increasing attention on studies of the nature of turbulent exchange, rather than on the exchange (i.e., the flux) itself. Studies of the nature of atmospheric turbulence require that experiments be performed in near-laboratory conditions, leading necessarily to the school of 'flat-earth, uniform-surface, steady-state micrometeorology' that tightly focuses attention on the need to derive answers to basic questions that can only be addressed in such circumstances. It must be remembered, however, that one reason for conducting such studies is the need to develop and demonstrate techniques to make both measurements and predictions in far less ideal circumstances, more typical of natural landscapes. It is such surfaces which constitute the most important target for studies of trace gas and particle exchange, and hence it is imperative to step beyond the constraints of laboratory-philosophy micrometeorology.

3. Co-spectral Similarity

The essence of the suggested approach is the assumption that the ratio of two fluxes can be closely approximated by the ratio of two characteristics of the corresponding turbulence fields. This is likely to be an acceptable assumption whenever the net transfer of the two quantities in question is accomplished by the same field of eddy motions.

Thus, in concept it is required that the two fluxes be of substances with the same distributions of sources (or sinks) at the surface, or that measurements of the turbulence be made sufficiently far above the surface that any source-sink inequalities become inconsequential.

The theory of co-spectral similarity has been discussed thoroughly elsewhere (Wyngaard and Coté, 1972). Here, prime attention will be on practical applications of the theory, rather than on the theory itself. However, special effort will be made to emphasize limitations, such as the difficulties arising over forests. It is assumed that standard siting requirements are met, concerning horizontal homogeneity, adequate fetch, and stationarity. Later discussion will address how some of these requirements may perhaps be relaxed.

Kaimal *et al.* (1972) summarize spectral data in terms of normalized frequency and atmospheric stability, for temperature and velocity components. The normalization of frequency involves the height of measurement z and the wind speed u. The height scale of direct relevance is that above the level of the appropriate zero plane, and thus need not necessarily be the same for all of the quantities of interest. For example, we might expect to find that the eddies transporting radon emitted from the soil beneath a canopy are more deeply penetrating (hence larger and slower) than those associated with momentum transfer (for which the effective level of action is usually in the upper part of the canopy). Such matters are discussed at length elsewhere (see Garratt, 1978; Hicks *et al.*, 1979; Hicks, 1985); for the present, it is sufficient to recognize that there is no *a priori* reason that all eddy transfer should be characterized by the same effective zero plane displacement levels. In the present context, care should be taken to ensure that potential errors are small.

Similar conceptual difficulties arise over surfaces that are irregularly vegetated or topographically complicated. In this case, inequalities in the horizontal distributions of effective sources and sinks will also cause transport by different eddies; in addition, streamlines will be affected by topographic relief in a manner that greatly complicates the direct application of standard eddy correlation or gradient techniques.

4. Method Development

In general, the surface heat energy budget can be written as

$$H + LE = R_n - S\,, \tag{1}$$

where H is the sensible heat flux, LE is the latent heat flux, and S is the rate of heat storage beneath the level of measurement. The Bowen ratio, β, is defined as H/LE, so that

$$H(1 + 1/\beta) = R_n - S\,. \tag{2}$$

Suppose that a measure of pollutant concentration standard deviation σ_c is measured in some selected frequency band, and that similarly constrained (i.e., defined by the same

frequencies) measures of temperature and humidity standard deviations are also obtained: σ_q and σ_T, respectively. If the flux of pollutant is F, then similarity principles dictate that

$$F/H \cong \sigma_c/c_p\sigma_T \tag{3}$$

and

$$H/LE = \beta = c_p\sigma_T/L\sigma_q\,. \tag{4}$$

From (4), trivial mathematical manipulation yields that

$$F \cong \sigma_c(R_n - S)/(c_p\sigma_T + L\sigma_q)\,. \tag{5}$$

Equation (4) provides a means for evaluating β without measuring gradients or covariances. Equation (5) yields an approximation of the flux F from imperfect (but matched) standard deviation data σ_c, σ_T, and σ_q, using measurements of net radiation as a basis. Net radiation can be measured using relatively simple instrumentation, without requiring anemometry or fast-response sensors. In daytime, the heat storage term S is typically less than 15% of R_n, and in most circumstances can be taken to be about 10% of R_n. Thus, (5) can be approximated as

$$v_d \cong 0.9(\sigma_c/C)R_n/(c_p\sigma_T + L\sigma_q)\,, \tag{6a}$$

where the deposition velocity v_d is defined as $-F/C$. (Note that the sign convention used here follows micrometeorological convention, so that turbulent fluxes are positive upwards.)

A somewhat simpler form of (6a) might be of special interest in circumstances in which the Bowen ratio β can be computed from external information, such as by use of a combination formula derived from agricultural or agrometeorological considerations. In this case, the need for specific humidity data to yield σ_q can be avoided, since (6a) can be rewritten as

$$v_d \cong 0.9(R_n/\overline{C})\,(\sigma_c/c_p\sigma_T)/(1 + 1/\beta)\,. \tag{6b}$$

The development above makes use of the equally-constrained turbulence-intensity standard deviations σ_T, σ_q, and σ_c as basic indicators of the corresponding fluxes of heat, moisture, and species mass. In practice, any of several indicators may be suitable, such as vertical differences ΔT, Δq, and ΔC over identical height intervals Δz. However, experience in initial field tests indicates that there is considerable benefit in using covariances with velocity components as indicator quantities. Work conducted so far has made use of vertical velocity to construct band-pass covariances C_{wT}, C_{wq}, and C_{wc}, which are used by direct substitution for σ_T, σ_q, and σ_c in the development given above, with no loss of generality:

$$v_d \cong 0.9(C_{wc}/C)R_n/(c_pC_{wT} + LC_{wq})\,, \tag{7a}$$

$$v_d \cong 0.9(R_n/C)\,(\overline{C}_{wc}/C_pC_{wT})/(1 + 1/\beta)\,. \tag{7b}$$

The revised relationships offer several advantages:

– The fundamental noise-rejection capabilities of covariance computations are used to advantage. This is of special importance in the case of a pollutant sensor (e.g., of SO_2, O_3, or NO_2), since unavoidable high-frequency noise contaminates all field measurements of σ_c regardless of the frequency band that is selected.

– The revised relations re-introduce the capability to differentiate between upward and downward fluxes.

– A simple band-pass filter can be applied to the shared signal used to compute the covariances. This helps ensure that the covariance indices are computed similarly, as is required by the underlying theory.

It should be noted that there is no requirement for either precise alignment of velocity sensors or for special analytical treatment to compensate for related measurement errors. The implications of this apparent lack of strong sensitivity to sensor orientation remain to be fully explored. For the present, it is sufficient to recognize that the method offers promise of some relaxation of stringent site and orientation requirements usually associated with micrometeorological field studies.

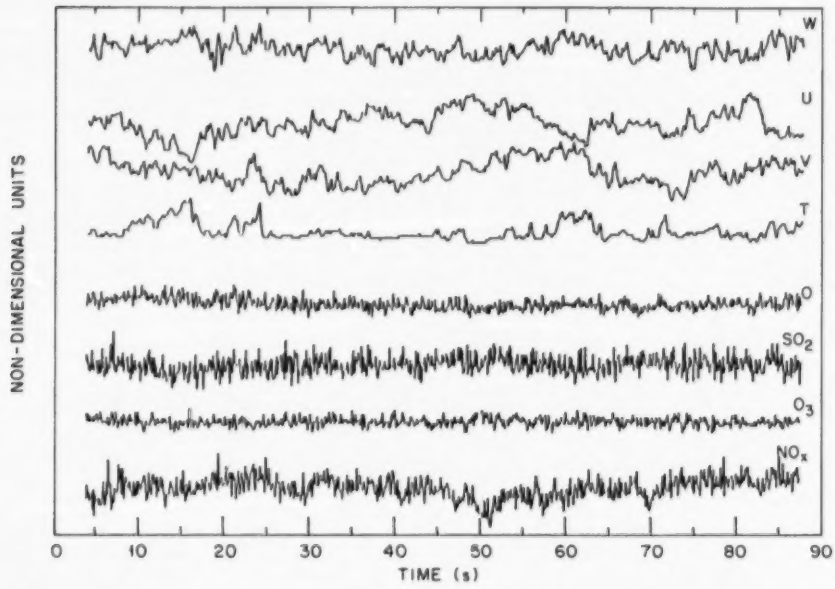

Fig. 1. An example of fast-response sensor outputs obtained during a recent field study conducted near State College, PA. All signals have mean values removed, using a 300 s recursive digital filter. The upper three traces are of wind velocity components: vertical, longitudinal and lateral. The fourth trace is of temperature, and the fifth represents humidity. The lowest three traces are of concentrations of sulfur dioxide, ozone, and nitrogen dioxide.

5. Spectra and Noise

Figure 1 is an illustration of records obtained using fast-response meteorological and air quality sensors during a recent study of dry deposition to agricultural crops, at State College, Pennsylvania. The traces demonstrate the high frequency noise that is a characteristic of all trace gas and aerosol sensors when operated near their limits of detectability. The speed of response required for normal day-time eddy correlation applications is about one second. For application in the way considered here, considerably slower time response may be adequate, as will be demonstrated later.

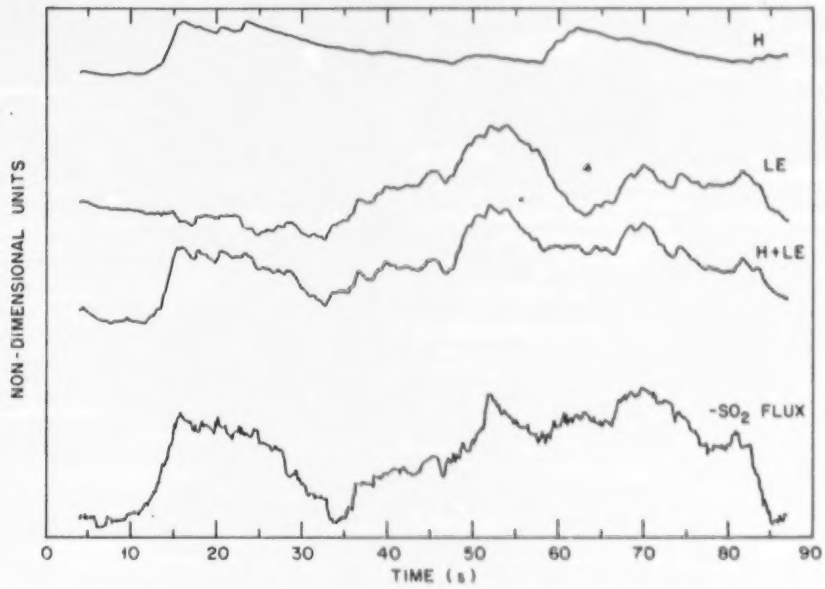

Fig. 2. 'Instantaneous' fluxes inferred from the fast-response traces shown in Figure 1, for sensible heat (H), latent heat (LE), and SO_2 exchange. Fluxes are computed as average covariances (using the vertical velocity), averaged over 20-s running mean. Note the close correspondence between the SO_2 exchange and the total turbulent heat flux $H + LE$.

Figure 2 demonstrates the ability of correlation techniques to extract meaningful signals from noisy data. The bottom curve is of running-mean covariances computed using the vertical velocity data of Figure 1 and the SO_2 concentrations. It is usually the time average (typically over 30-min periods) of such data that is of main interest. For the present, it is instructive to note the strong correlation between the SO_2 covariance record and that of sensible heat (H) and latent heat (LE) derived similarly (as smoothed covariances with temperature and humidity, respectively), and especially the strong correspondence with the total turbulent heat exchange, $H + LE$. It is this similarity of

TABLE I

Examples of data generated by a test of the theory of similarity methods for deducing pollutant deposition from radiation data and heat budget considerations, using slow-responding pollution sensors. All data are for 30-min runs, above a forest canopy. Data are quoted for 1, 3, 10, and 30 s response time sensors. Units for global (R_g) net radiation (R_n), sensible heat flux (H) and latent heat flux (LE) are W m^{-2}. All other quantities are normalized to unity for 'perfect' sensors. Fluxes F1, F2, and F3 are of SO_2, small particles (0.5–0.7 μm diameter), and larger particles (0.7–1.2 μm), respectively. The remaining quantities are standard deviations, also normalized, and in the same sequence.

	H	LE	F_1	F_2	F_3	ST	S_q	S_1	S_2	S_3
1500–1530, 2 May, 1983, R_g = 775, R_n = 540										
	224	279	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1 s	220	274	1.00	1.00	1.00	0.99	0.99	1.00	0.99	0.98
3 s	205	259	0.99	1.00	1.00	0.98	0.98	1.00	0.99	0.95
10 s	169	228	0.97	0.94	0.92	0.94	0.94	0.99	0.97	0.91
30 s	71	149	0.90	0.84	0.80	0.85	0.86	0.96	0.95	0.87
1530–1600, 2 May, 1983, R_g = 640, R_n = 465										
	245	205	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1 s	242	202	0.99	1.00	1.03	0.98	0.99	0.99	0.94	0.94
3 s	231	192	0.97	0.83	1.27	0.96	0.96	0.97	0.85	0.85
10 s	197	160	0.92	0.83	0.92	0.91	0.92	0.95	0.69	0.72
30 s	151	119	0.77	0.83	0.89	0.84	0.84	0.90	0.58	0.59
1600–1630, 2 May, 1983, R_g = 576, R_n = 385										
	166	124	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1 s	162	120	1.00	0.98	0.92	0.98	0.99	0.94	0.94	0.94
3 s	147	108	1.01	0.84	0.60	0.96	0.96	0.88	0.84	0.84
10 s	108	78	0.88	0.66	0.27	0.91	0.91	0.78	0.66	0.69
30 s	62	44	0.33	0.79	0.21	0.82	0.82	0.70	0.51	0.56
1630–1700, 2 May, 1983, R_g = 473, R_n = 302										
	136	92	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1 s	132	88	0.91	0.89	0.99	0.98	0.98	0.94	0.89	0.95
3 s	121	80	0.71	1.20	0.87	0.96	0.96	0.89	0.84	0.85
10 s	95	60	0.63	0.21	0.63	0.90	0.90	0.81	0.69	0.72
30 s	51	31	0.15	1.01	0.48	0.81	0.81	0.71	0.52	0.56
1700–1730, 2 May 1983, R_g = 352, R_n = 196										
	109	82	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1 s	108	80	0.99	0.74	0.83	0.98	0.99	0.95	0.94	0.94
3 s	99	74	0.95	1.02	0.65	0.96	0.96	0.89	0.85	0.83
10 s	79	59	0.73	0.38	0.99	0.91	0.90	0.78	0.68	0.69
30 s	47	39	0.29	−0.32	1.38	0.67	0.83	0.67	0.52	0.54
1730–1800, 2 May 1983, R_g = 243, R_n = 103										
	125	49	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1 s	123	47	0.99	0.90	1.10	0.98	0.96	0.93	0.94	0.94
3 s	114	43	0.96	0.96	0.87	0.96	0.94	0.87	0.84	0.85
10 s	98	36	0.82	0.19	1.37	0.91	0.89	0.75	0.67	0.69
30 s	55	21	0.57	0.30	1.10	0.82	0.79	0.62	0.50	0.53

turbulent exchange processes that underlies the techniques suggested here, and it is the inbuilt noise-rejection capability of eddy-correlation that permits the approach to be applied in the case of noisy pollutant sensors.

Table I presents an example of results obtained in a field test conducted at the Walker Branch Watershed forest meteorology field site on the Department of Energy's Oak Ridge (Tennessee) reservation. The data were obtained during a multilaboratory 'CORE' research experiment (see Hales *et al.*, 1987) conducted in collaboration with Argonne National Laboratory, Pennsylvania State University and the EPA Atmospheric Sciences Research Laboratory. The tabulation includes information on temperature, humidity, atmospheric sulfur concentration, and particle concentrations in two size ranges, approximately 0.5–0.7 and 0.7–1.2 μm diameter. The effect of using pollutant sensors with relatively slow response times has been simulated by smoothing records obtained with fast-response sensors to produce 1, 3, 10, and 30-s averages prior to computation.

The simulation demonstrates the expected noise reduction achieved by data averaging. The smoothing accomplished by signal averaging, often by application of capacitive feedback in electronic circuits, is a major reason that monitoring instruments are normally designed to have relatively slow response (i.e., minutes rather than seconds).

6. Heat Storage

The term S in Equations (1), (2), and (5) has so far been approximated as $0.1R_n$. The matter of heat storage and the evaluation of S has been investigated at the Walker Branch Watershed following similar procedures to earlier studies reported by Hicks *et al.* (1975) and Baldocchi *et al.* (1985). In the present instance, the Walker Branch field site is seen as an extreme test of the importance of S, since the site is forested and independent measurement of S in such circumstances is difficult. In practice, S is made up of several terms, primarily the heat storage S_1 involved in the biomass:

$$S_1 = Mc_b(\partial T_b/\partial t)\,, \tag{8}$$

where M is the quantity of biomass per unit surface area, c_b is the appropriate specific heat, and $\partial T_b/\partial t$ is the rate of change of biomass temperature T_b with time t. Heat storage associated with the air mass below the level of measurement (S_2) is also likely to be important, especially when foliage is sufficiently dense that subcanopy air temperatures rise to very high levels:

$$S_2 \simeq \rho c_p h(\partial T_a/\partial t)\,, \tag{9}$$

where h is the height of measurement of H and LE, T_a is the temperature of the air beneath the level h, and ρ is air density. The heat storage associated with changes of specific humidity (S_3) need also to be considered:

$$S_3 = h(\rho c_w)T_a(\partial q/\partial t)\,, \tag{10}$$

where c_w is the specific heat of water vapor.

A final term, G, concerns heat conduction directly into the ground. G is typically small in circumstances of a dense vegetative cover (such as at the Walker Branch field site, where the canopy is a 25-m oak-hickory forest), but for crops, grassland, and bare soil, G is far more important than either of S_1, S_2, or S_3.

It is possible to summarize the likely magnitudes of the various terms contributing to the net storage term S (as is evident in the present diagrams, and as discussed by Thom, 1975, and Baldocchi *et al.*, 1985), or to compute them using detailed sub-canopy measurements or models (e.g., McCaughey, 1985). Table II is intended to provide an indication of the relative magnitudes for sunny, summer conditions.

TABLE II

Estimates of heat storage terms contributing to the surface energy balance for measurements made at a height of 5 m above the vegetation in different circumstances. All values are expressed as a proportion of the available net radiation, R_n.

	Biomass storage S_1	Air thermal storage S_2	Air humidity storage S_3	Ground heat conduction G
Forest	10%	1%	1%	1%
Corn	4%	0	0	6%
Pasture	0	0	0	10%
Bare soil	0	0	0	15%

Sources: Baldocchi *et al.* (1985); Hicks *et al.* (1983); Hicks *et al.* (1972); Pruitt *et al.* (1973); Dyer and Hicks (1970).

Figure 3 demonstrates the possible consequences of neglecting S, or alternatively of applying the first-order correction represented by the assumption that $S \simeq 0.1R_n$, as in Equations (6) and (7). The data contributing to Figure 3 enable direct evaluation of S in Equation (1). Figure 4 relates the term S to the rate of change of canopy temperature with time $\partial T_b/\partial t$. There is considerable uncertainty associated with the determination of S, since it is computed as a small residual among several imperfectly-measured quantities (especially H and LE). As discussed elsewhere (Hicks *et al.*, 1983), Figure 4 does not show all the data; averages that are not significantly different from zero are omitted, since they do not contribute significantly to elucidating the underlying physics.

The biomass temperature data used to obtain Figures 3 and 4 were intensive, repetitive measurements using a hand-held infrared thermometer at many levels in the canopy. Canopy temperature profiles derived using these data have been presented elsewhere (Hicks, 1985). In practice, such direct measurements of biomass temperature are rarely available, and in-canopy air temperatures are typically used instead (Baldocchi *et al.* (1985) present a relevant discussion regarding the same site). It appears likely that such air temperature data would be sufficiently accurate indicators of biomass temperature for the present purposes, although doubtlessly some errors will arise.

The validity of the interpretations given above is illustrated by the line drawn through

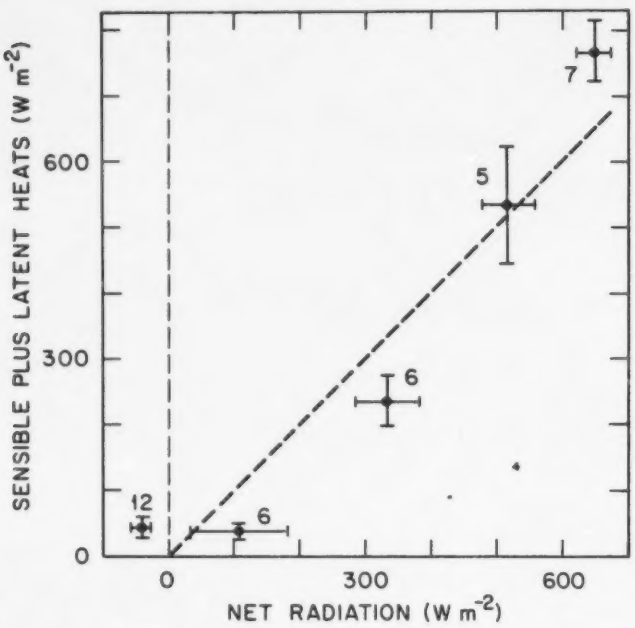

Fig. 3. Results of surface heat budget conducted at the NOAA/ARATDD forest field site in Oak Ridge, during May 1983. The line represents equality between the sum of sensible (H) and latent (LE) heat fluxes, and net radiation (R_n). Numbers indicate the size of the sample from which the plotted averages and standard errors are computed.

the data of Figure 3. The slope of the line is determined by theory, given independent measurement of the biomass per unit area of the canopy in question (41 kg m^{-2}) and an assumed specific heat of 1 cal g^{-1} °C^{-1}. The intercept remains undetermined because in reality neither canopy biomass temperature nor canopy air temperature alone is a completely adequate measure of the effective canopy temperature.

7. Simulation Results

The data quoted in Table I are typical of results obtained in daytime, convective conditions. The nocturnal case presents substantially greater difficulty, and has yet to be addressed in as much detail as the daytime case.

Table I also lists normalized covariances, which are directly related to the corresponding eddy fluxes, as derived from data smoothed by a range of time constants, as long as 30 s. Concentration standard deviations yielded by the same data-treatment procedures are also listed. The problems associated with the blind application of Equation (5) (or its equivalents), using standard deviations of turbulent fluctuations as

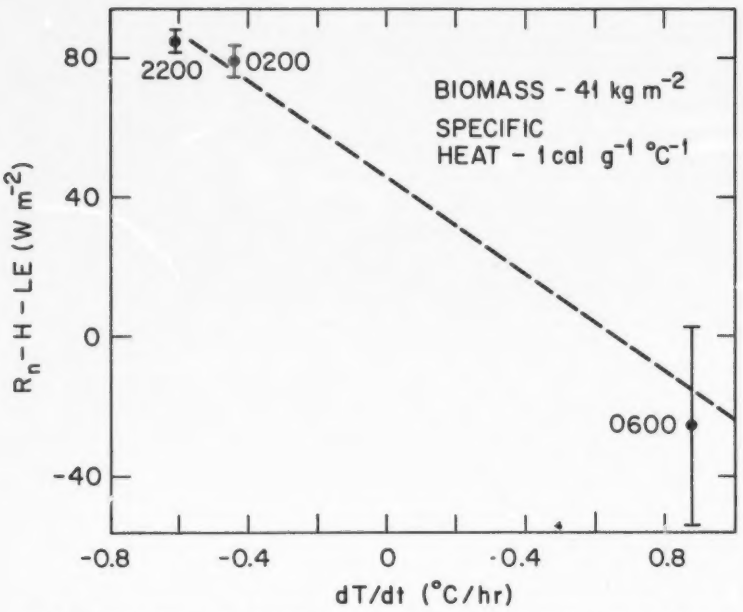

Fig. 4. The dependence of the surface heat flux residual ($R_n - H - LE$) or the time rate of change of canopy temperature. The line drawn corresponds to measured canopy biomass (41 kg m^{-2}) and an assumed specific heat of 1 cal g^{-1} °C^{-1}.

a basis for apportioning available heat energy and for evaluating pollutant fluxes, are evident from inspection of the values tabulated.

Figure 5 illustrates the consequences of high-frequency noise on the general utility of standard deviations as a basis for calculations. The values plotted are normalized geometric mean standard deviations for temperature (humidity values are indistinguishable), SO_2 and small particles (in the two bands used here, 0.5–0.7 μm and 0.7–1.2 μm diameter). As high-frequency noise is rejected by smoothing with increasing time constant, the effect on particle standard deviations is seen to be greatest. At the other extreme, the effect on temperature (and humidity) standard deviations is the least among the presently observed quantities. This is seen as a direct consequence of the ease with which temperature and humidity records can be obtained using modern sensors.

It should be noted that for particles, the problem is exacerbated by effects associated with poor counting statistics. The roll-off associated with the SO_2 data is less than that associated with the measurement of particle concentration, but greater than that for the meteorological variables. In this context, the use of covariances (with w) instead of standard deviations as indicators of total turbulent transport seems especially attractive, sicne the influence of high-frequency noise is then minimized.

Figure 6 extends the present considerations to covariances. The effect of sample response time on the evaluation of eddy fluxes is illustrated using SO_2 signals, and

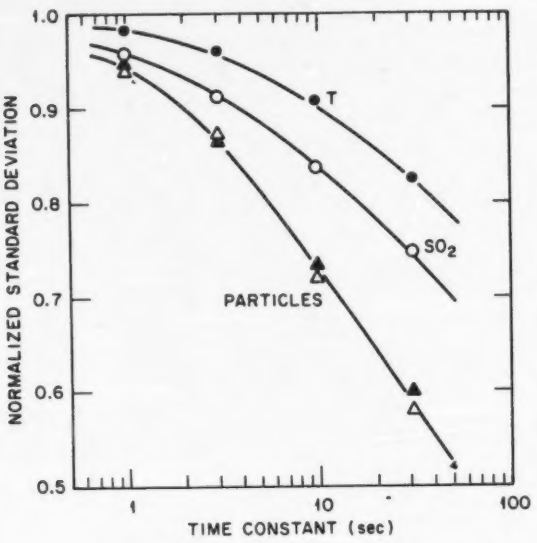

Fig. 5. The effect of sampling response time on apparent standard deviation associated with temperature (dots), sulfur dioxide (circles), and particle concentration (crosses) records. Data are normalized to values obtained from 'raw' data from fast-response sensors.

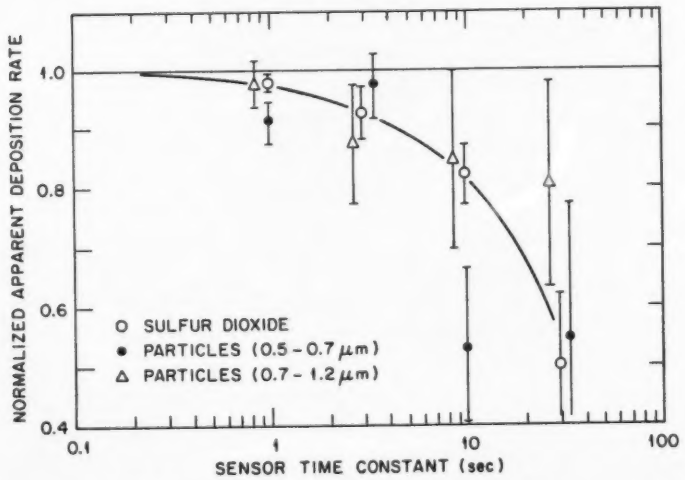

Fig. 6. The effect of sampling response time on the apparent vertical flux of SO_2 and small particles. Data plotted are normalized to values obtained from 'raw' data obtained using fast-response sensors.

particle records in the same size ranges as previously: 0.5–0.7 μm and 0.7–1.2 μm. As expected, covariances are less affected by inadequate sensor response than are standard deviations. It should be emphasized, however, that fluxes are the consequence of much faster fluctuations at night than in daytime, and hence the promise indicated by Figure 5 should not be extended beyond the daytime conditions in which the data were obtained.

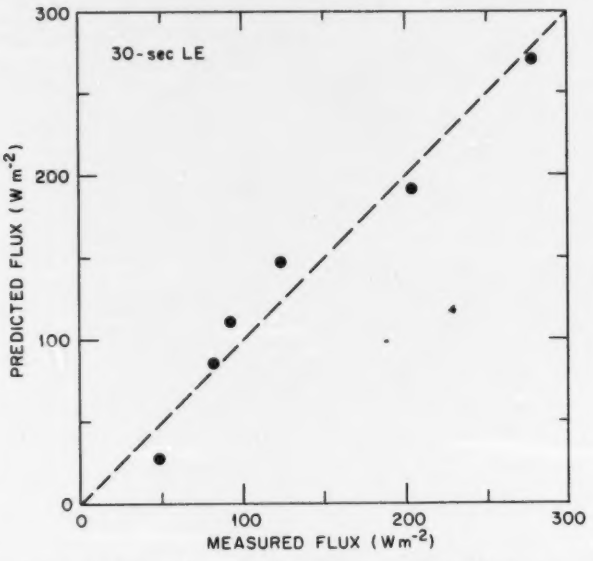

Fig. 7. A comparison of latent heat fluxes derived by application of (5), with direct-measurements made by eddy correlation. The heat storage term is assumed to be a constant 10% of the net radiation.

Figure 7 illustrates the ability of the similarity methods advocated here to provide accurate estimates of vertical fluxes. For purposes of illustration, Figure 7 plots estimated latent heat fluxes, *LE*, derived from using the most smoothed data (30-s time constant) listed in Table I, against the actual values measured by eddy correlation. In this case, the use of standard deviation data appears warranted, because of the relative ease with which a clean analog signal proportional to water vapor concentration can be produced, even at high frequencies (> 1 Hz). (For these studies, a Lyman-alpha hygrometer was employed.) Some scatter is evident in the diagram, but this scatter appears to be random and is much as expected on the basis of experience with comparisons between any pair of devices intended to measure the same turbulent flux.

8. Conclusions

The similarity methods discussed here are intended to permit fluxes of some trace species to be inferred from knowledge of other fluxes if appropriate gradient, turbulence

intensity or covariance data are available to serve as a linkage. The constraint imposed by the surface heat energy balance involving (primarily) net radiation, sensible heat, latent heat of evaporation, and heat storage provides an opportunity to bypass the need for a direct flux measurement. In practice, net radiation is easily measured, using straightforward sensors available from commercial sources. No special micrometeorological skills are required for their proper use, although technical competence is certainly necessary. The method of present interest uses net radiation as a basis for calculations, and employs similarity principles first to derive the sensible heat flux and then to infer a dry deposition flux from knowledge of pollutant turbulence characteristics.

In concept, no fully-implemented micrometeorological turbulent flux data are required. Thus, the possibility exists (but remains to be fully explored) that the methods might be applicable in less ideal terrain than might otherwise be feasible.

Investigations of the methods described here are presently continuing; however, it is already apparent that the techniques summarized above are indeed capable of producing answers with reduced need for fully-expanded micrometeorological support, and without the usual eddy correlation sensor requirement for 1-s response or better. However, the analyses conducted so far point to some difficulties. If variances are used as the basis for computation, the effects of random noise propagate through the system in a manner that necessarily adds to the real signal variance, such that σ_c will always tend to be overestimated and, hence, so will v_d. This source of error is much the same as that which arises with other methods relying on single signal variances rather than on gradients or covariances.

It is also clear that the use of variance data as a basis for computations using the similarity/heat budget approach leads to uncertainty concerning the direction of the flux, precisely as in the case of direct analysis of variance in conventional meteorological applications.

An alternative method, in which the standard deviations in Equations (3)–(7) are replaced by covariances computed using some other, well-measured meteorological variable, appears capable of minimizing effects resulting from random noise, since by definition noise will be uncorrelated with any other signal. Furthermore, information on the sign of the vertical flux is then retained.

Acknowledgement

This work was conducted under the sponsorship of the U.S. Environmental Protection Agency, as a contribution to the National Acid Precipitation Assessment Program.

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